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User's Manual for FEMOM3DS Version 1.0

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1. INTRODUCTION

FEMOM3DS is a computer code written in FORTRAN 77 to compute electromagnetic(EM) scattering characteristics of a three dimensional object with complex materials (figure 1) using combined Finite Element Method (FEM)/Method of Moments (MoM) technique[1]. This code uses the tetrahedral elements, with vector edge basis functions for FEM in the volume of the cavity and the triangular elements with the basis functions similar to that described in [2], for MoM at the outer boundary. By virtue of FEM, this code can handle any arbitrarily shaped three-dimensional cavities filled with inhomogeneous lossy materials. The basic theory implemented in the code is given in Appendix 1.

The User's Manual is written to make the user acquainted with the operation of the code. The user is assumed to be familiar with the FORTRAN 77 language and the operating environment of the computers on which the code is intended to run. The organization of the manual is as follows. Section 1 is the introduction. Section 2 explains the installation requirements. The operation of the code is given in detail in Section 3. Two example runs, the first EM scattering characteristics of a dielectric sphere and the second EM scattering characteristics form an inlet cavity are demonstrated in Section 4. Some test cases are presented in Section 5 to show the flexibility of the code. The test cases were run by the authors to validate the code. Users are encouraged to try these cases to get themselves acquainted with the code.

2. INSTALLATION OF THE CODE

The distribution disk of FEMOM3DS is 3.5" floppy disk formatted for IBM compatible PCs. It contains a file named `femom3ds.tar.gz`. This file has to be transferred to any UNIX machine via `ftp` using binary mode. On the UNIX machine, use the following commands to get all the files.

```
gunzip femom3ds.tar.gz
tar -xvf femom3ds.tar
```

This creates a directory `FEMOM3DS-1.0`, which in turn contains the

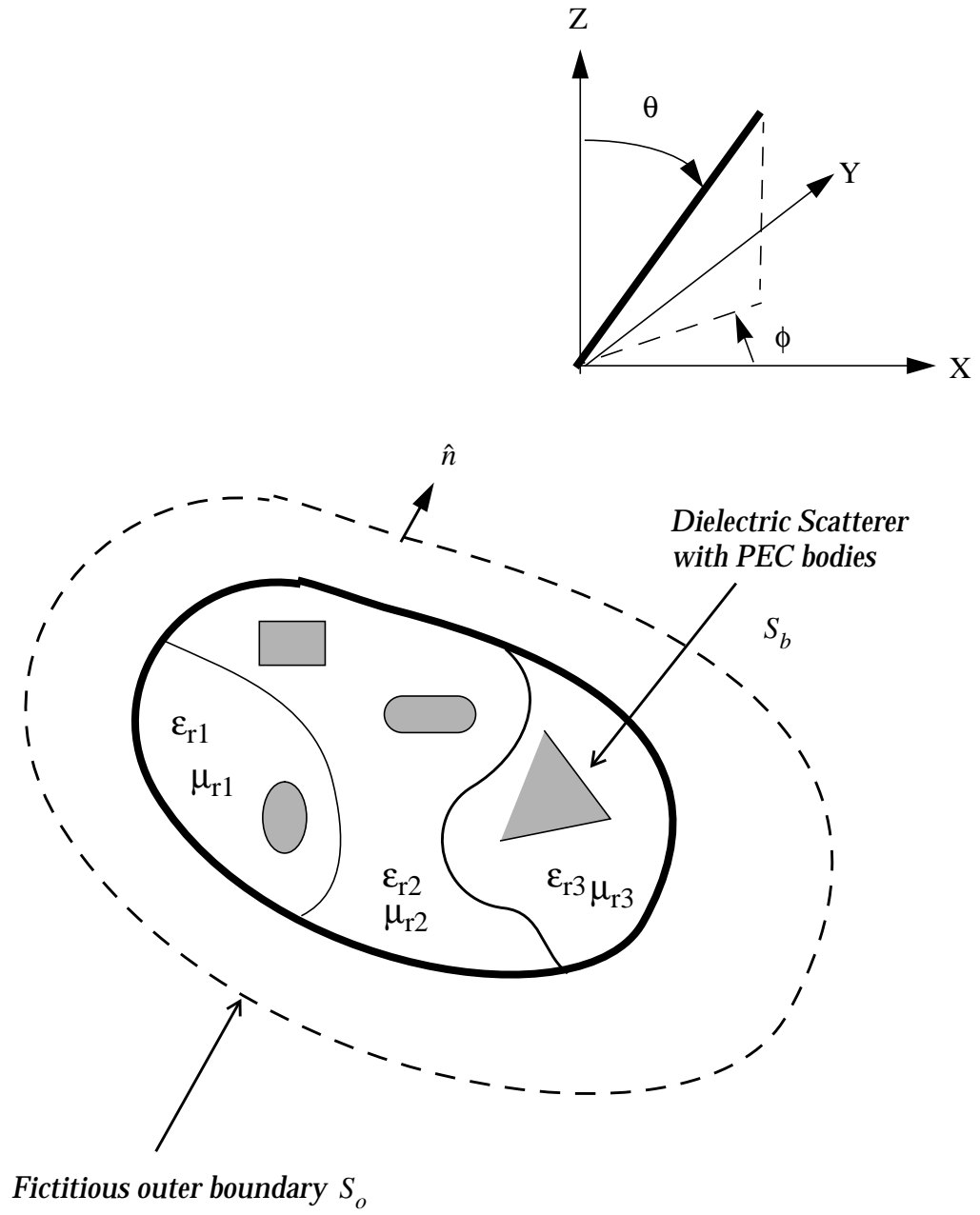


Figure 1 Illustration of the scattering body with surface, S_b enclosed by a fictitious outer surface S_o , which is used to terminate the FEM computational domain.

subdirectories, `FEMOM3DS` (source files for the main code), `PRE_FEMOM3DS` (source files for preprocessing code), `Example1` and `Example2`. As the code is written in FORTRAN 77, with no particular computer in mind, the source code in these directories should compile on any computer architecture without any problem. The code was successfully compiled on a CONVEX machine, and the compilation can be done by using a `makefile` file for the different machines such as SUN, SGI etc. The complete listing of the directories in the distribution disk is given in Appendix 2.

3.0 OPERATION OF THE CODE

The computation of EM scattering characteristics from a specific geometry with FEMOM3DS is a multi-stage process as illustrated in figure 2. The geometry of the problem has to be constructed with the help of any commercial Computer Aided Design (CAD) package. In our case, we used COSMOS/M[3] as our geometry modeler and meshing tool. Once the object geometry is modelled, PEC surfaces are to be identified for implementing proper boundary conditions. As FEMOM3DS uses edge based basis functions, the nodal information supplied by most of the meshing routines cannot be readily used. Hence, a preprocessor `PRE_FEMOM3DS` is written to convert the nodal based data into edge based data and then is given as input to FEMOM3DS. For the convenience of the users, who use different CAD/meshing packages other than COSMOS/M, `PRE_FEMOM3DS` accepts the nodal based data in a generic format also. The procedures involved for using COSMOS/M input data file or generic input data file are explained below.

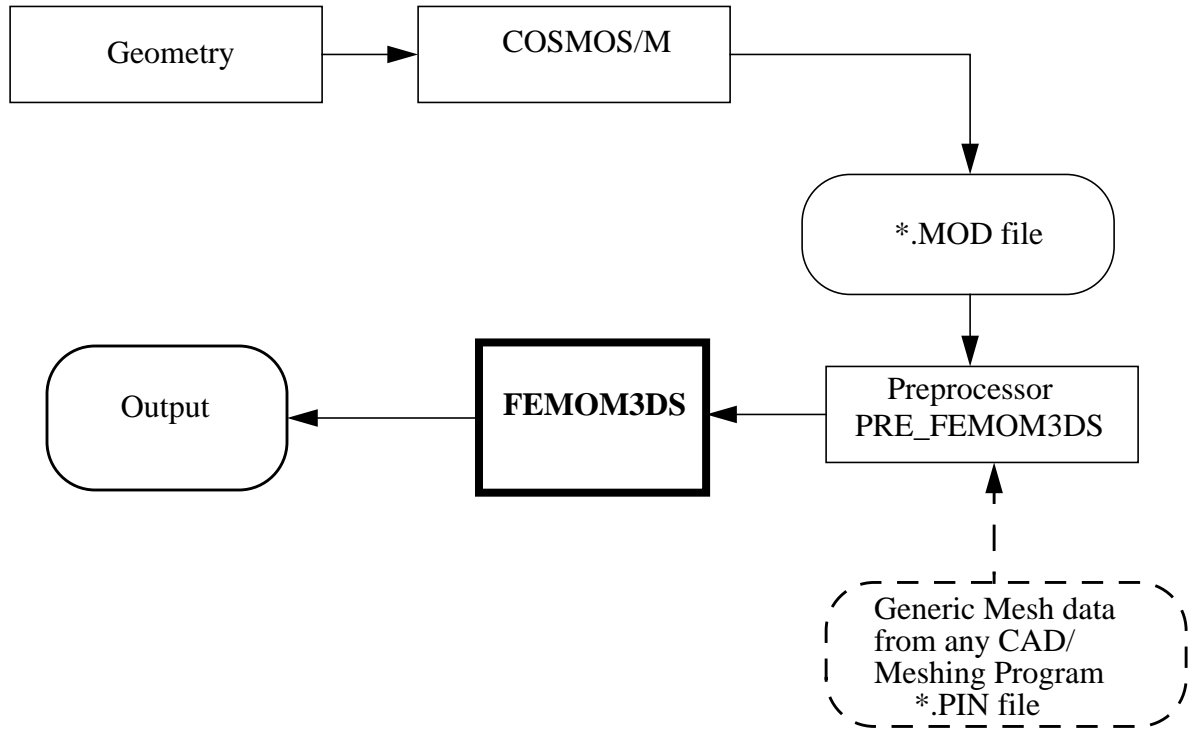


Figure 2 Flow chart showing the various steps involved in using FEMOM3DS

With the help of COSMOS/M, the geometry is constructed and meshed with tetrahedral elements. The user is assumed to be familiar with COSMOS/M package and its features. Once the mesh is generated, one needs to identify the following to impose proper boundary conditions:

- (a) tetrahedral elements with different material parameters¹,
- (b) elements on PEC surfaces
- (c) elements on the outer boundary (for the purpose of calculating the electric current)

This is done using the available features in COSMOS/M. Sample *.SES files of COSMOS/M which illustrate these features are given in Appendix 3. Finally the *.MOD file is generated with the required mesh information. PRE_FEMOM3DS accepts the *.MOD file as input and generates the required edge based data.

For users, who can do geometry modelling and meshing of the model with any other CAD package, the nodal based information is required to be placed in a file *problem.PIN*,

1. COSMOS/M has a feature by which it can group tetrahedral elements with different material properties into different groups. For a generic file input, the user has to specify the material property index for each tetrahedral element to indicate its material property group (see Appendix 4).

where *problem* is the name of the problem under consideration. The format required for *.PIN file is given in Appendix 4. Note that all the dimensions of the geometry are assumed to be in centimeters.

The PRE_FEMOM3DS code gives the following prompts:

```
pre_femom3ds
```

Give the problem name:

The problem name is the user defined name for the particular problem under consideration.

COSMOS file (1) or GENERIC (2) file?

If you are using *.MOD file from COSMOS/M, give 1 or using the generic input data file explained above, give 2.

PRE_FEMOM3DS generates the following files with required edge based information.

(a) *problem_nodal.dat* - Node coordinates and the node numbers for each element

(b) *problem_edges.dat* - Information on edges, such as nodes connecting each edge, etc.

(c) *problem_surfed.dat* - Information on number of edges on each surface

(d) *problem.POUT* - General information on the mesh.

The files (a) to (c) are used as input for FEMOM3DS. Users need not interact or modify the above files.

After PRE_FEMOM3DS is run, all but one input data file required for FEMOM3DS are ready. FEMOM3DS expects to find *problem.MAT* file which contains the material constants information required for the volume elements. The format of the *problem.MAT* is as given below:

N_g ,	Maximum number of material groups
ϵ_{r1}, μ_{r1}	Complex relative permittivity, complex relative permeability respectively
ϵ_{r2}, μ_{r2}	for material groups 1, 2, 3,, N_g
.	
.	
$\epsilon_{rN_g}, \mu_{rN_g}$	

In the PRE_FEMOM3DS, all the tetrahedral elements are given the material group index. The material parameters given in *problem.MAT* are read into FEMOM3DS and the proper material parameters are assigned to each tetrahedral element according to its material property

index. Once the *problem*.MAT is ready, FEMOM3DS code can be run. The FEMOM3DS code gives the following prompts:

```
femom3ds
```

```
Give the problem name :
```

```
This name should be the same as given for PRE_FEMOM3DS
```

```
Frequency (GHZ) :
```

This is the frequency of operation. If the dimensions of the problem are in wavelengths, frequency should be specified as 30 GHz as FEMOM3DS assumes that all dimensions are in centimeters.

```
Monostatic or Bistatic ?
```

```
Give 1 for Monostatic, 2 for Bistatic
```

This is to specify whether to calculate monostatic electromagnetic scattering or bistatic electromagnetic scattering. In the case of monostatic scattering the observation point is in the same direction as that of the incident wave, whereas in the bistatic case, the direction of the incident wave is fixed and the EM scattering is observed at different directions. Hence one has to specify the direction of the incident wave for bistatic scattering.

For Bistatic scattering

```
Incident angles, theatai(degs), phi i(degs)
```

θ_i and ϕ_i give the direction of the incident plane wave.

```
Give 0 for H-polarization
```

```
Give 90 for E-polarization
```

This is to specify the polarization of the incident plane wave.

```
Plane of incidence-
```

```
Give 1 for fixed phi and phi(degs)
```

```
2 for fixed theta and theta(degs)
```

This specifies the angle of incidence for the incident wave. Backscatter calculations can be done at a constant ϕ -plane or at a constant θ -plane by choosing either 1 or 2 and giving the value of ϕ or θ at the plane of interest respectively.

Give angle of incidence-
start,end,increment (degs) :

This specifies range of angles for which backscatter calculations are to be performed. For a constant ϕ -plane, these are values of θ and for constant θ -plane these are values of ϕ .

FEMOM3DS generates the file *problem.OUT*, which contains information on CPU times for matrix generation, matrix fill, the parameters for electromagnetic scattering data. FEMOM3DS also generates another file *problem_bicgd.DAT* which contains information on convergence history of diagonally preconditioned biconjugate gradient algorithm used to solve the matrix equations.

4.0 SAMPLE RUNS

Two example runs are illustrated in this section. They are selected to illustrate some of the features of FEMOM3DS.

Example 1 : Bistatic Scattering from a dielectric sphere

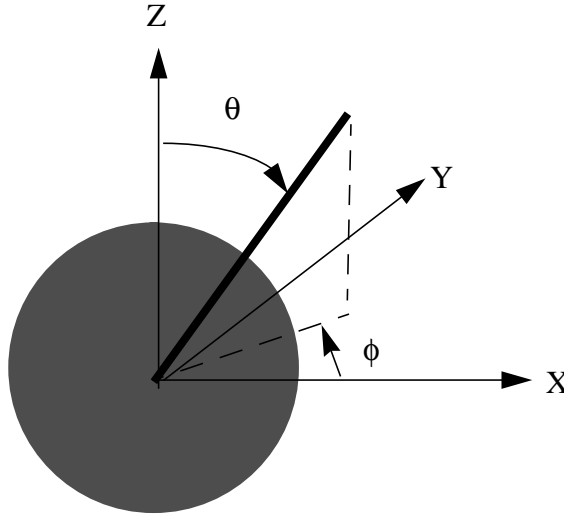


Figure 3 Dielectric sphere of radius 0.16cm with $\epsilon_r = 4.0$, $\mu_r = 1.0$

A dielectric sphere of radius 0.16cm, with $\epsilon_r = 4.0$ and $\mu_r = 1.0$. Bistatic scattering is calculated with the plane wave incident from the direction $\theta = 180^\circ$ and $\phi = 0^\circ$.

First the PRE_FEMOM3DS

```
cjr@magellan:{37} pre_femom3ds
Give the problem name :
sp
COSMOS file(1) or GENERIC(2) file ? :
1
Opening file :sp.MOD
Nodes=          52
No of elements=          135

Read the following data
Nodes=          52
Elements=        135
Elements on surface 1=          88
Max number of material groups=          1

Forming the edges !!! Be patient !!!

Number of edges=          230
Order of the FEM matrix- nptrx=          230

*****

Number of nodes=          52
Number of elements=          135
Number of total edges=          230
Number of elements on Surface 1=          88
Number of edges on surface 0(pec)=          0
Number of edges on surface 1=          132
Max number of maetrial groups=          1

*****

STOP:

The sp.MAT file for this problem is given below:
1
(4.0,0.0) (1.0,0.0)
```

And then FEMOM3DS :

```
Give the problem name :
sp
Frequency (GHZ) :
30.0
Monostatic or Bistatic ?
Give 1 for Monostatic, 2 for Bistatic
2
Incidence angles, theatai(degs),phii(degs)
180.0 0.0
Give 0 for H-polarization
Give 90 for E-polarization
0.0

Plane of incidence/obsr(Mono) - Obser(Bi)-
Give 1 for fixed phi and phi(deg)
2 for fixed theta and theta(degs)
1 0
Give angle of incidence/obsr(Mono)- obsr(Bi):
start, end, increment
0 180 10
Reading the input !!
Finished reading the data
Order of the FEM matrix-net=          230
Total matrix order=net1=net+nsptrx1=          362

Order of the MoM matrix, nsptrx1=          132
*****
*                                          *
*                                          *
*          FEMoM3DS(Version 1.0)          *
*          Problem : sp                    *
*                                          *
*                                          *
*****

BiSTATIC RADAR CROSS SECTION

Frequency (GHz)          =    30.00000
Order of the FEM-MoM matrix=    362
Order of the MoM matrix  =    132

Incident Angles
  Thetai(degs)=    180.0000
  Phii(degs)  =           0.
```

```

H-Polarization
Sweep through theta : phi =          0
Start(degs)=          0
Stop(degs) =          180
Increment(degs)=          10
  Number of non zeros in amat(zmatrices)=          2924
Time to fill FEM matrix=  0.1569319
  Zmatrixeh
Time to fill zmatrixeh=  6.2719822E-02
  Non zeros after zmateh=          3584
  zmatrixej
Time to fill zmatrixej=  22.97427
  Non-zeros after zmatej=          21008
  zmatrixem
Time to fill zmatrixem=  30.85342
Time to fill zmatrices (secs)=  53.89322
Total no of non zeros after adding zmatrices=          38432
CONVERGENCE ACHIEVED in          282 iterations
Residual Norm=  5.5933034E-04
Solution time(secs)=  33.03685

```

Ang(deg)	SigHH(dB)	SigHE(dB)
0	-9.876550	-58.94287
10	-10.01219	-59.61543
20	-10.43050	-60.21722
30	-11.14991	-60.79119
40	-12.20645	-61.43825
50	-13.66489	-62.27667
60	-15.64468	-63.39064
70	-18.38787	-64.75037
80	-22.48750	-66.08037
90	-30.15921	-66.86278
100	-37.94263	-66.89146
110	-26.00531	-66.64410
120	-21.50988	-66.69263
130	-18.91976	-67.33405
140	-17.24439	-68.63268
150	-16.12831	-70.31013
160	-15.40722	-71.30753
170	-14.99740	-70.54909
180	-14.85810	-68.86301

The complete session of this run on a CONVEX C-220 along with all the files is kept in the directory /FEMOM3DS-1.0/Example1.

Example 2: Monostatic Scattering from a rectangular inlet cavity

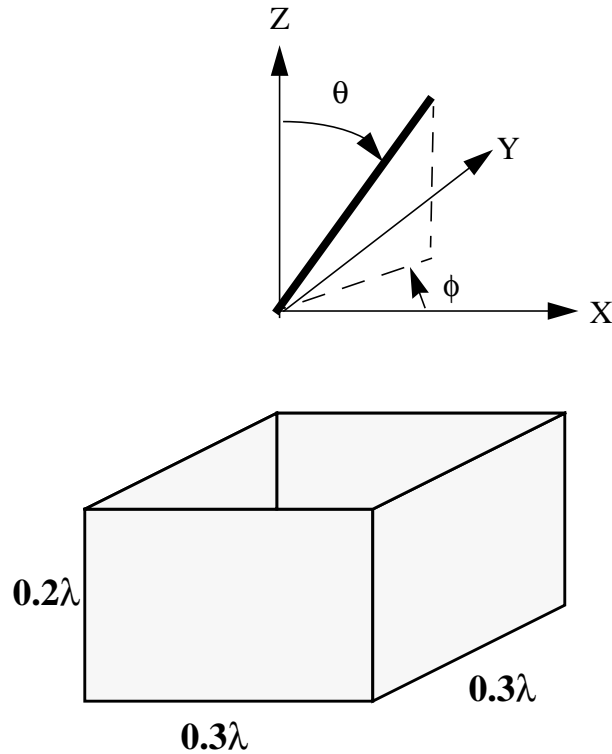


Figure 4 Rectangular inlet cavity

The geometry of the rectangular inlet cavity is shown in figure 3. The cavity is open on one end and is closed at the bottom. Monostatic scattering is calculated.

First the PRE_FEMOM3DS

```

Give the problem name :
inlet
COSMOS file(1) or GENERIC(2) file ? :
1
Opening file :inlet.MOD
Nodes=          101
No of elements=          283

```

```

Read the following data
Nodes=          101
Elements=        283
Elements on surface 1=          160
Max number of material groups=          1

```

Forming the edges !!! Be patient !!!

```

Number of edges=          463
Order of the FEM matrix- nptrx=          263

```

```

Number of nodes=          101
Number of elements=          283
Number of total edges=          463
Number of elements on Surface 1=          160
Number of edges on surface 0(pec)=          200
Number of edges on surface 1=          240
Max number of maetrial groups=          1

```

STOP:

The inlet .MAT file for this problem is given below:

```

1
(1.0,0.0) (1.0,0.0)

```

And then FEMOM3DS :

```

Give the problem name :
inlet
Fequency (GHZ) :
30.0
Monostatic or Bistatic ?
Give 1 for Monostatic, 2 for Bistatic
1

```

```

Give 0 for H-polarization
Give 90 for E-polarization
0

```

```

Plane of incidence/obsr(Mono) - Obser(Bi)-
Give 1 for fixed phi and phi(deg)

```

```

        2 for fixed theta and theta(degs)
1 0
    Give angle of incidence/obsr(Mono)- obsr(Bi):
    start, end, increment
0 180 10

    Reading the input !!
    Finished reading the data
    Order of the FEM matrix-net=                263
    Total matrix order=net1=net+nsptrx1=        503

    Order of the MoM matrix, nsptrx1=            240

*****
*                                                    *
*                                                    *
*          FEMoM3DS(Version 1.0)                    *
*          Problem : inlet                          *
*                                                    *
*                                                    *
*****

MONOSTATIC RADAR CROSS SECTION

Frequency (GHz)                =    30.00000
Order of the FEM-MoM matrix=    503
Order of the MoM matrix      =    240
H-Polarization
Sweep through theta : phi =    0
Start(degs)=                  0
Stop(degs) =                  180
Increment(degs)=               10
    Number of non zeros in amat(zmatrices)=        3179
Time to fill FEM matrix=    0.2643120
    Zmatrixelh
Time to fill zmatrixelh=    7.8801036E-02
    Non zeros after zmateh=        3379
    zmatrixelj
Time to fill zmatrixelj=    79.19982
    Non-zeros after zmatej=        60979
    zmatrixelm
Time to fill zmatrixelm=    48.21815
Time to fill zmatrices (secs)=    127.4995
Total no of non zeros after adding zmatrices=        70579

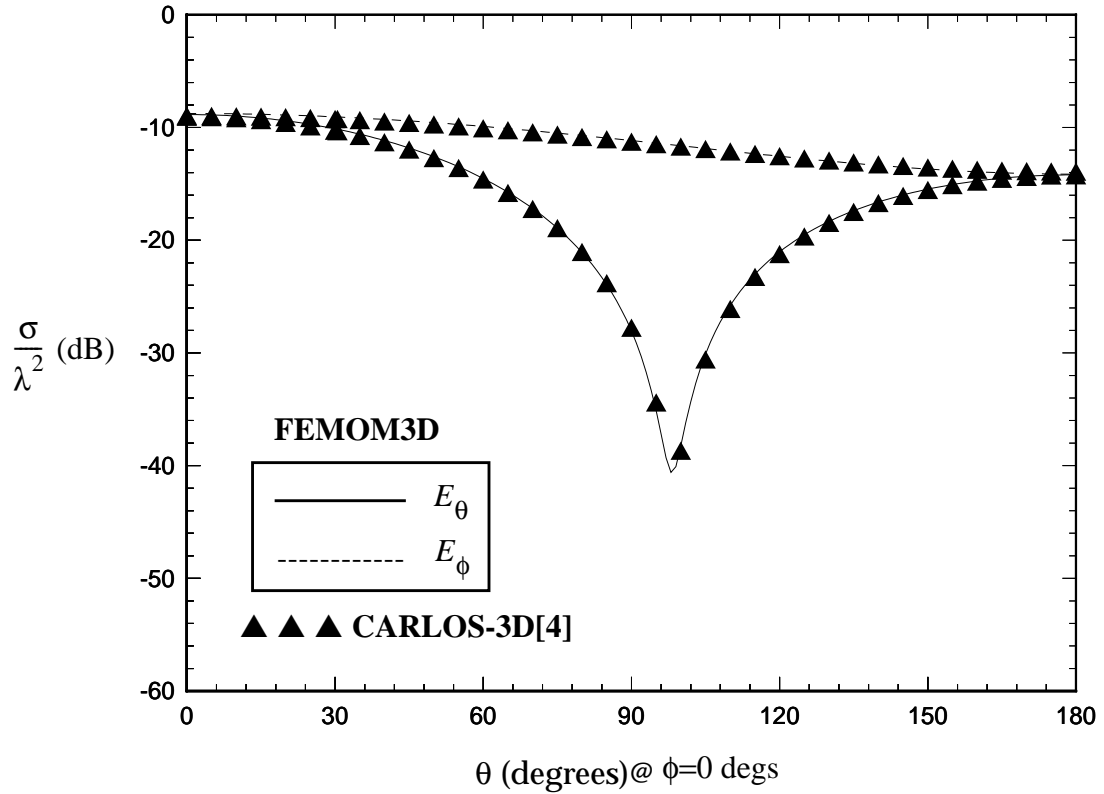
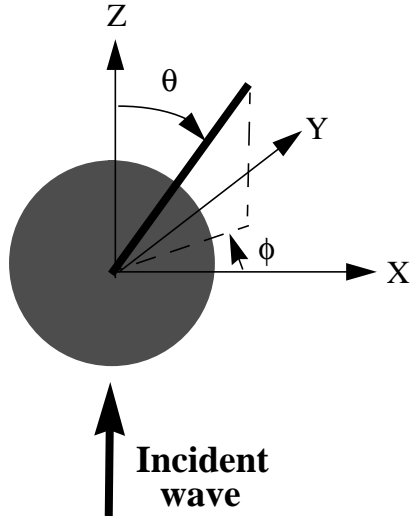
```

	Ang(deg)	SigHH(dB)	SigHE(dB)	Time(secs)
	0	-0.3081026	-55.40033	67.74269
	10	-0.4520388	-52.60987	60.19102
	20	-0.9098186	-49.97753	57.31442
	30	-1.734988	-47.91700	54.19781
	40	-2.999914	-46.49533	55.80737
	50	-4.769355	-45.82520	53.95328
	60	-7.047320	-45.95884	54.81299
	70	-9.630483	-46.89593	63.12811
	80	-11.76193	-48.70896	58.05768
	90	-12.20721	-51.62140	55.32001
	100	-10.86643	-55.89311	66.16351
	110	-8.766810	-59.68416	57.74194
	120	-6.633481	-57.03788	68.58752
	130	-4.791438	-53.42066	56.93665
	140	-3.356782	-50.92786	59.78656
	150	-2.333028	-49.05974	54.35376
	160	-1.669239	-47.60739	57.40320
	170	-1.302017	-46.63602	63.49841
	180	-1.183381	-46.32928	55.77466

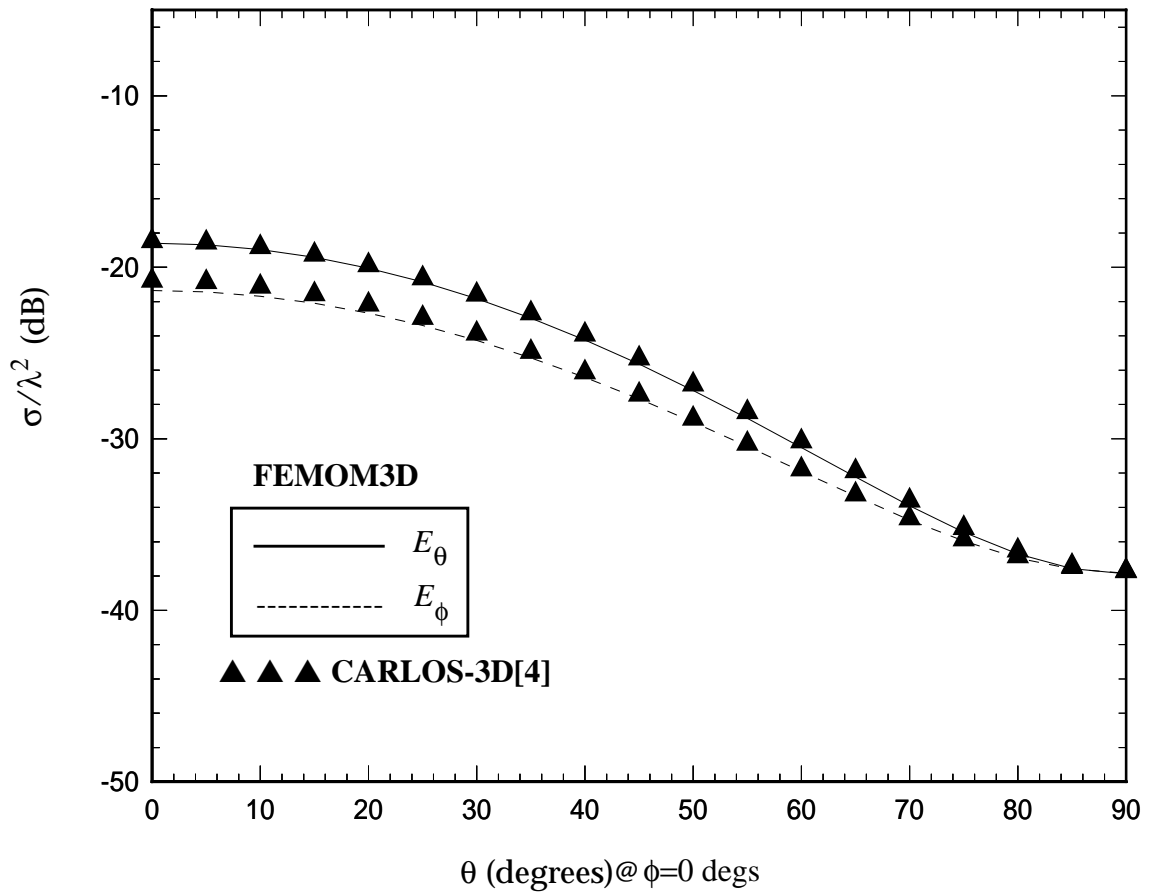
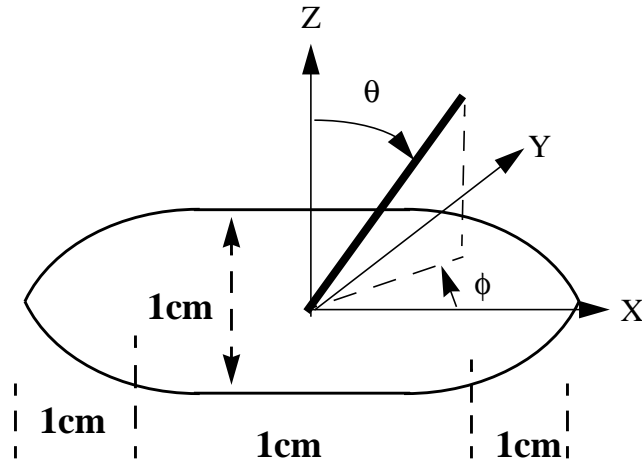
The complete session of this run on a CONVEX C-220 along with all the files is kept in the directory ./FEMOM3DS-1.0/Example2.

5.0 TEST CASES

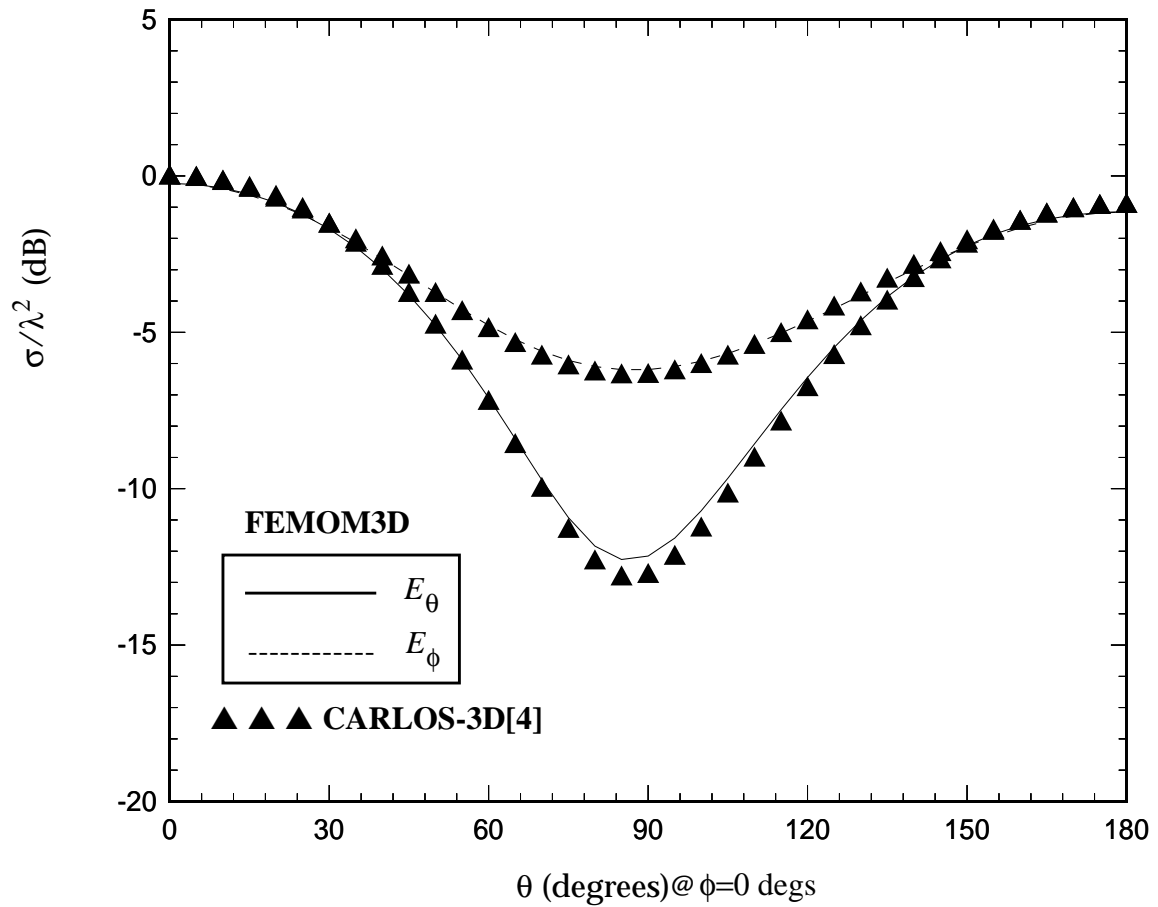
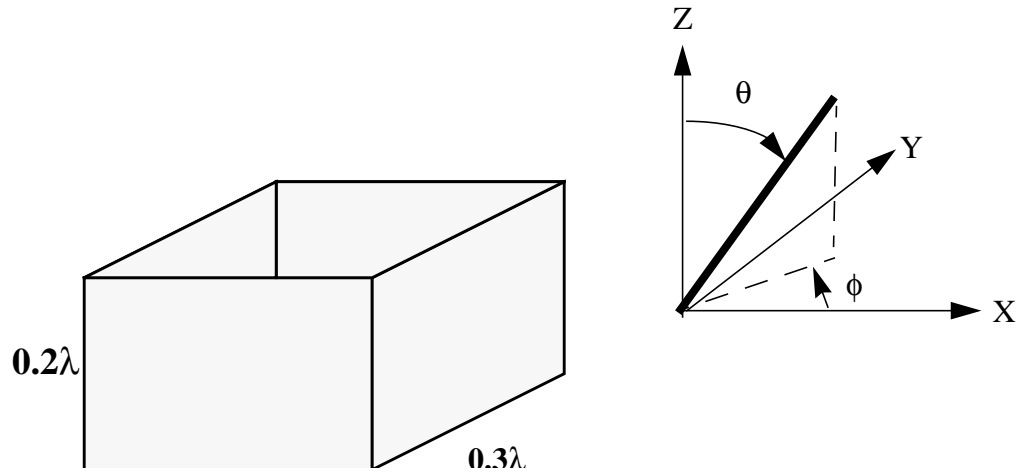
Test Case 1: Bistatic RCS of a dielectric sphere ; ($ka=1$, $\epsilon_r=4.0$, $\theta_{in}=180^\circ$, $\phi_{in}=0^\circ$)



Test Case 2: Monostatic RCS of a dielectric ogive ; (Freq=6.0GHz, $\epsilon_r=2.0$)



Test Case 3 : Monostatic RCS of a rectangular inlet cavity with opening on one side



6.0 CONCLUDING REMARKS

The usage of FEMOM3DS code is demonstrated so that the user can get acquainted with the details of using the code with minimum possible effort. As no software can be bug free, FEMOM3DS is expected to have hidden bugs which can only be detected by the repeated use of the code for a variety of geometries. Any comments or bug reports should be sent to the authors. As the reported bugs are fixed and more features added to the code, future versions will be released. Information on future versions of the code can be obtained from

Electromagnetics Research Branch (MS 490)
Flight Electronics and Technology Division
NASA-Langley Research Center
HAMPTON VA 23681

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Appendix 1

Theory for FEMOM3DS

This appendix is intended to give a brief description of the theory behind the code. The geometry of the structure to be analyzed is shown in figure 1. S_b represents the outer surface of the 3D object, S_o represents the area of the fictitious outer boundary to be used for terminating the FEM computational domain. The electric field inside the computational domain satisfies the vector wave equation[5]

$$\nabla \times \left(\frac{1}{\mu_r} \nabla \times \mathbf{E} \right) - k_o^2 \epsilon_r \mathbf{E} = 0 \quad (1)$$

where ϵ_r and μ_r are the relative permittivity and relative permeability of the medium. The time dependency of $\exp(j\omega t)$ is assumed through out this report. To facilitate the suitable solution of the partial differential equation in (1) via FEM, multiply equation (1) with a vector testing function \mathbf{T} and integrate over the volume of the computational domain. By applying suitable vector identities, equation(1) can be written in its weak form as,

$$\iiint_V \frac{1}{\mu_r} (\nabla \times \mathbf{T}) \cdot \left(\frac{1}{\mu_r} \nabla \times \mathbf{E} \right) dv - k_o^2 \epsilon_r \iiint_V \mathbf{T} \cdot \mathbf{E} dv = \iiint_V \nabla \cdot \left(\mathbf{T} \times \frac{1}{\mu_r} \nabla \times \mathbf{E} \right) dv \quad (2)$$

Applying the divergence theorem to the right hand side of equation(2), the volume integral is written as the surface integral over the surface S_o terminating the FEM computational domain.

$$\iiint_V \frac{1}{\mu_r} (\nabla \times \mathbf{T}) \cdot (\nabla \times \mathbf{E}) dv - k_o^2 \epsilon_r \iiint_V \mathbf{T} \cdot \mathbf{E} dv = - \iint_{S_o} \mathbf{T} \cdot \left(\hat{n} \times \frac{1}{\mu_r} \nabla \times \mathbf{E} \right) ds \quad (3)$$

where \hat{n} is the unit outward normal to the surface S_o .

To discretize the above volume and surface integrals, the FEM computational domain is subdivided into small volume tetrahedral elements. The electric field is expressed in terms of vector edge basis functions[2] which enforce the divergenceless condition of the electric field implicitly

$$\mathbf{E} = \sum_{i=1}^6 e_i \mathbf{W}_i \quad (4)$$

where e_i 's are the unknown coefficients associated with each edge of the tetrahedral element and \mathbf{W}_i 's are the basis functions and are given in detail in [6]. The testing function \mathbf{T} is taken to be the same set of basis functions as given in equation (4), i.e.,

$$\mathbf{T} = \mathbf{W}_j \quad j=1,2,3,4,5,6 \quad (5)$$

The discretization of the FEM computational volume automatically results in discretization of surface S_o in triangular elements. The evaluation of the surface integrals over the outer boundary is evaluated either by using Method of Moments(MoM) or Absorbing Boundary Conditions (ABCs).

Evaluation of surface integral over S_o - MoM formulation :

At the fictitious outer boundary the electric field is subjected to the condition that the fields are continuous across the boundary, i.e.,

$$\mathbf{E}|_{at S_o^+} = \mathbf{E}|_{at S_o^-} \quad (6)$$

where S_o^+ denotes the outer side of S_o and S_o^- denotes the inner side of S_o . The electric field $\mathbf{E}|_{at S_o^-}$ is the field quantity being evaluated in the computational volume through FEM. The electric field outside S_o is evaluated explicitly using the following equation[5, eq.3-83]:

$$\mathbf{E}|_{at S_o^+} = -\nabla \times \mathbf{F} - j\omega\mu_o \mathbf{A} + \frac{1}{j\omega\mu_o} \nabla \nabla \cdot \mathbf{A} + \mathbf{E}_{inc} \quad (7)$$

where

$$\mathbf{A} = \text{Magnetic Vector Potential} = \frac{1}{4\pi} \int_{S_o} \frac{\mathbf{J} \exp(-jk_o |\mathbf{r} - \mathbf{r}_o|)}{|\mathbf{r} - \mathbf{r}_o|} ds \quad (8)$$

$$\mathbf{F} = \text{Electric Vector Potential} = \frac{1}{4\pi} \int_{S_o} \frac{\mathbf{M} \exp(-jk_o |\mathbf{r} - \mathbf{r}_o|)}{|\mathbf{r} - \mathbf{r}_o|} ds \quad (9)$$

and

$$\mathbf{E}_{inc} = \text{Incident Electric Field} = \mathbf{E}_i \exp[j(k_x x + k_y y + k_z z)]$$

where

$$\mathbf{E}_i = \hat{x}E_{xi} + \hat{y}E_{yi} + \hat{z}E_{zi} \quad (10)$$

and

$$E_{xi} = \cos\theta_i \cos\phi_i \cos\alpha - \sin\phi_i \sin\alpha \quad (11)$$

$$E_{yi} = \cos\theta_i \sin\phi_i \cos\alpha + \cos\phi_i \sin\alpha \quad (12)$$

$$E_{zi} = -\sin\theta_i \cos\alpha \quad (13)$$

$$k_x = k \sin\theta_i \cos\phi_i \quad (14)$$

$$k_y = k \sin\theta_i \sin\phi_i \quad (15)$$

$$k_z = k \cos\theta_i \quad (16)$$

\mathbf{J} and \mathbf{M} are assumed to be equivalent electric and magnetic currents respectively at the outer surface S_o . θ_i and ϕ_i indicate the direction of the incident field. The terms with the magnetic vector potential contribute to the electric field outside V due to the equivalent electric current radiating into free space. Similarly the term with electric vector potential contribute to the electric field outside V due to the equivalent magnetic current radiating into free space (figure 5).

Substituting equation (7) into equation (6) and multiplying by a testing function $\hat{n} \times \mathbf{T}$ on both sides and integrate over the surface S_o , results in:

$$\begin{aligned} \iint_{S_o} (\hat{n} \times \mathbf{T}) \cdot \mathbf{E} ds = & - \iint_{S_o} (\hat{n} \times \mathbf{T}) \cdot (\nabla \times \mathbf{F}) ds - j\omega\mu_o \iint_{S_o} (\hat{n} \times \mathbf{T}) \cdot \mathbf{A} ds \\ & + \frac{1}{j\omega\epsilon_o} \iint_{S_o} (\hat{n} \times \mathbf{T}) \cdot (\nabla \nabla \cdot \mathbf{A}) ds + \iint_{S_o} (\hat{n} \times \mathbf{T}) \cdot \mathbf{E}_{inc} ds \quad (17) \end{aligned}$$

After some mathematical manipulations [7, pp.42], [8, pp.135], and substituting equations (8) and (9) in the above equation, it can be rewritten as:

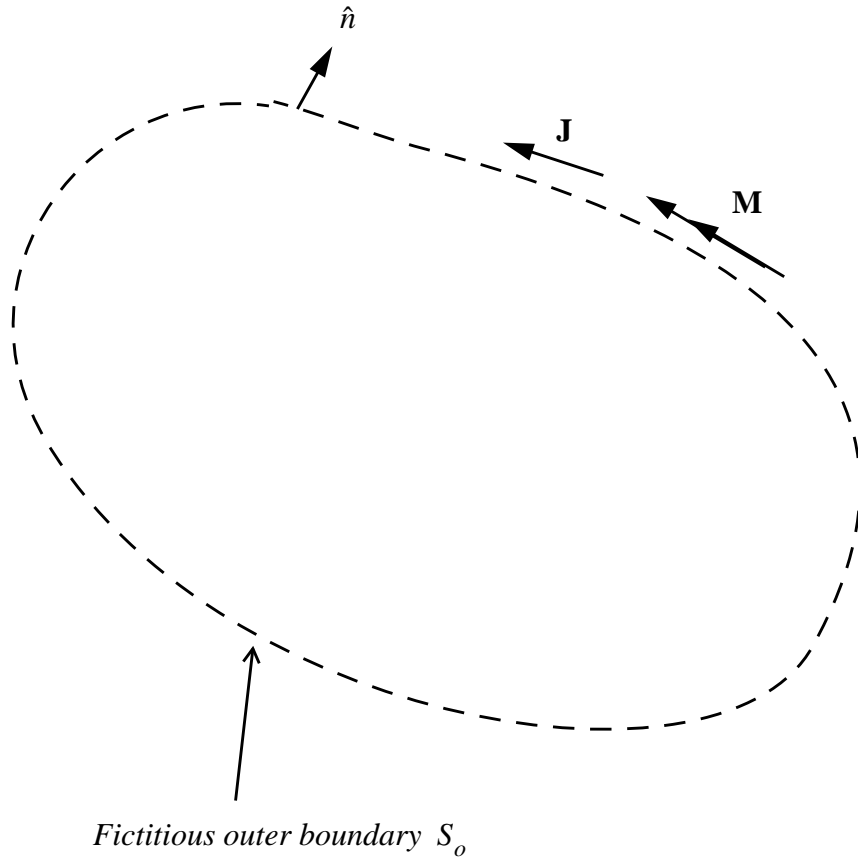


Figure 5 Equivalent current representation of the outer surface S_o

$$\begin{aligned}
& \frac{1}{2} \iint_{S_o} (\hat{n} \times \mathbf{T}) \cdot \mathbf{E} ds + \frac{1}{4\pi} \iint_{S_o} (\hat{n} \times \mathbf{T}) \cdot \left(\oint\!\!\!\oint_{S_o} \mathbf{M} \times \nabla' G ds' \right) ds \\
& + \frac{j\omega\mu_o}{4\pi} \iint_{S_o} (\hat{n} \times \mathbf{T}) \cdot \left(\iint_{S_o} \mathbf{J} G ds' \right) ds + \frac{1}{j\omega\epsilon_o(4\pi)} \iint_{S_o} \{ \nabla \cdot (\hat{n} \times \mathbf{T}) \} \{ \iint_{S_o} (\nabla \cdot \mathbf{J}) G ds' \} ds \\
& = \iint_{S_o} (\hat{n} \times \mathbf{T}) \cdot \mathbf{E}_{inc} ds
\end{aligned} \tag{18}$$

where $\oint\!\!\!\oint$ indicates that the singular point has been removed and

$$G = \frac{\exp(-jk_o|\mathbf{r} - \mathbf{r}_o|)}{|\mathbf{r} - \mathbf{r}_o|} \tag{19}$$

Equation (18) is written in a matrix form by choosing the proper basis functions for \mathbf{M} and \mathbf{J} and accordingly using the testing function $\hat{n} \times \mathbf{T}$. Within each surface triangle, the surface currents can be expressed as

$$\mathbf{M} = \mathbf{E} \times \hat{n} = - \sum_{i=1}^3 e_i (\hat{n} \times \mathbf{W}_i) \tag{20}$$

$$\mathbf{J} = \sum_{i=1}^3 I_i (\hat{n} \times \mathbf{W}_i) \tag{21}$$

and the testing function as

$$\hat{n} \times \mathbf{T} = \hat{n} \times \mathbf{W}_j \quad j=1,2,3 \tag{22}$$

In equation (20), e_i represents the same unknown coefficient as in equation (4) and in equation (21) I_i represents the unknown coefficient for the surface electric current density. In equations (20) and (21), it is interesting to note that, the vector edge basis functions \mathbf{W}_i , which are initially used for electric field are used to represent the surface current densities in the form of $\hat{n} \times \mathbf{W}_i$. The expansion functions \mathbf{W}_i are used to build tangential continuity into the field representation. In contrast, the cross product of \hat{n} with these functions results in another set of basis functions which guarantee normal continuity with zero curl and nonzero divergence and hence are ideally suited for representing surface current densities[2]. During

the current investigation, it has been observed that the roof top basis functions for triangular pathes used by Rao[7] and the basis functions used here proved to be numerically identical to each other confirming the above point of view.

Equations (20-22) are substituted in equation (18) and integrated over all the triangular patch elements on surface S_o to obtain the following matrix equation:

$$\begin{bmatrix} M_1 \end{bmatrix} \{e\} + \begin{bmatrix} M_2 \end{bmatrix} \{I\} = \{b_1\} \quad (23)$$

where

$$\begin{bmatrix} M_1 \end{bmatrix} = \frac{1}{2} \iint_{S_o} (\hat{n} \times \mathbf{T}) \cdot \vec{E} ds + \frac{1}{4\pi} \iint_{S_o} (\hat{n} \times \mathbf{T}) \cdot \left(\iint_{S_o} \mathbf{M} \times \nabla' G ds' \right) ds \quad (24)$$

$$\begin{bmatrix} M_2 \end{bmatrix} = \frac{j\omega\mu_o}{4\pi} \iint_{S_o} (\hat{n} \times \mathbf{T}) \cdot \left(\iint_{S_o} \mathbf{J} G ds' \right) ds + \frac{1}{j\omega\epsilon_o(4\pi)} \iint_{S_o} \{ \nabla \cdot (\hat{n} \times \mathbf{T}) \} \left\{ \iint_{S_o} (\nabla \cdot \mathbf{J}) G ds' \right\} ds \quad (25)$$

and

$$\{b_1\} = \iint_{S_o} (\hat{n} \times \mathbf{T}) \cdot \mathbf{E}_{inc} ds \quad (26)$$

The singularities in evaluating the integrals in equation (25) are handled analytically by using the closed form expressions given in[9].

Using Maxwell's equation $\nabla \times \mathbf{E} = -j\omega\mu_o\mu_r\mathbf{H}$, the surface integral on the right hand side of the equation (3) can be written as

$$-\iint_{S_o} \mathbf{T} \cdot \left(\hat{n} \times \frac{1}{\mu_r} \nabla \times \mathbf{E} \right) ds = \iint_{S_o} \mathbf{T} \cdot (\hat{n} \times \mathbf{H}) ds \quad (27)$$

By equivalence principle, it can be noted that $\mathbf{J} = \hat{n} \times \mathbf{H}$ on the surface S_o . Substituting this into equation (27), equation (3) can be rewritten as:

$$\iiint_V \frac{1}{\mu_r} (\nabla \times \mathbf{T}) \cdot (\nabla \times \mathbf{E}) dv - k_o^2 \epsilon_r \iiint_V \mathbf{T} \cdot \mathbf{E} dv = \iint_{S_o} \mathbf{T} \cdot \mathbf{J} ds \quad (28)$$

Substituting equations (4),(5) and (14) in the above equation and integrating over all the tetrahedral elements to evaluate the volume integrals on the left hand side and integrating over all the surface triangular elements to evaluate the surface integral on the right hand side, it can

be written in a matrix form as

$$\begin{bmatrix} F_1 \end{bmatrix} \{e\} + \begin{bmatrix} F_2 \end{bmatrix} \{I\} = \{0\} \quad (29)$$

where

$$\begin{bmatrix} F_1 \end{bmatrix} = \iiint_V \frac{1}{\mu_r} (\nabla \times \mathbf{T}) \cdot (\nabla \times \mathbf{E}) dv - k_o^2 \epsilon_r \iiint_V \mathbf{T} \cdot \mathbf{E} dv \quad (30)$$

$$\begin{bmatrix} F_2 \end{bmatrix} = \iint_{S_o} \mathbf{T} \cdot \mathbf{J} ds \quad (31)$$

and $\{0\}$ is the null vector. The evaluation of the volume integrals over a tetrahedral element is given in detail in [6].

Equations (23) and (29) are combined to form a system matrix equation:

$$\begin{bmatrix} F_1 & F_2 \\ M_1 & M_2 \end{bmatrix} \begin{bmatrix} e \\ I \end{bmatrix} = \begin{bmatrix} 0 \\ b_1 \end{bmatrix} \quad (32)$$

In the above system matrix F_1 and F_2 are sparse matrices and M_1 and M_2 are dense matrices and also the total matrix is complex and non-symmetric in nature. This matrix equation is solved using a diagonally preconditioned biconjugate gradient algorithm, where it is necessary to store only the non zero entries of the matrix.

The solution of equation (32), enables the computation of the electric field in the computational volume and the equivalent magnetic and electric current densities on the surface terminating the computational domain. Using the equivalent electric and magnetic current densities on the surface terminating the computational domain, the scattered electric far field is computed as [5]

$$\begin{aligned} \mathbf{E}_{fscat}(\mathbf{r}) \Big|_{r \rightarrow \infty} &= -jk_o \eta_o \frac{\exp(-jk_o r)}{4\pi r} \iint (\hat{\theta}\hat{\theta} + \hat{\phi}\hat{\phi}) \cdot \mathbf{J}(x', y') \exp(jk_o \sin(\theta(x' \cos \phi + y' \sin \phi) + z' \cos \theta)) dx' dy' \\ &+ jk_o \frac{\exp(-jk_o r)}{4\pi r} \iint (-\hat{\theta}\hat{\phi} + \hat{\phi}\hat{\theta}) \cdot \mathbf{M}(x', y') \exp(jk_o \sin(\theta(x' \cos \phi + y' \sin \phi) + z' \cos \theta)) dx' dy' \end{aligned} \quad (33)$$

where (r, θ, ϕ) are the spherical coordinates of the observation point. The radar cross section is given by

$$\sigma = \lim_{r \rightarrow \infty} 4\pi r^2 \frac{|\mathbf{E}_{fscat}(\mathbf{r})|^2}{|\mathbf{E}_{inc}(\mathbf{r})|^2} \quad (34)$$

Appendix 2

Listing of the Distribution Disk

/FEMOM3DS-1.0

```
total 32
drwxr-xr-x  2 cjr           512 Jul 29 14:52 Example1/
drwxr-xr-x  2 cjr           512 Jul 29 14:51 Example2/
drwxr-xr-x  2 cjr        1024 Jul 29 14:52 FEMOM3DS/
drwxr-xr-x  2 cjr        1024 Jul 29 14:51 PRE_FEMOM3DS/
```

/FEMOM3DS-1.0/PRE_FEMOM3DS

```
total 528
-rw-r--r--  1 cjr        6712 Jul 29 14:46 cosmos2fem.f
-rw-r--r--  1 cjr       5358 Jul 28 14:30 edge.f
-rw-r--r--  1 cjr         624 Jun 10 15:47 makefile
-rw-r--r--  1 cjr       1651 Jul 28 14:27 meshin.f
-rw-r--r--  1 cjr       1715 Jun 10 14:41 param0
-rw-r--r--  1 cjr         800 Nov 15 1994 pmax.f
-rwxr-xr-x  1 cjr    472284 Jul 28 14:30 pre_femom3ds*
-rw-r--r--  1 cjr       7719 Jun 10 16:25 pre_femom3ds.f
-rw-r--r--  1 cjr       2798 Jun 10 15:46 surfel.f
```

/FEMOM3DS-1.0/FEMOM3DS

```
total 752
-rw-r--r--  1 cjr       5151 Jul 23 14:39 analy.f
-rw-r--r--  1 cjr       4583 Jul 23 14:39 basis.f
-rw-r--r--  1 cjr       4220 Jul 28 15:53 bicgdnf.f
-rw-r--r--  1 cjr       2186 Jul 23 14:42 elemdb.f
-rw-r--r--  1 cjr       3616 Jul 23 14:43 elmatr.f
-rw-r--r--  1 cjr       3026 Jul 23 14:44 excit.f
-rwxr-xr-x  1 cjr    529008 Jul 28 15:53 femom3ds*
-rw-r--r--  1 cjr     17609 Jul 28 15:25 femom3ds.f
-rw-r--r--  1 cjr       3028 Jul 23 14:44 fourierxy.f
-rw-r--r--  1 cjr         801 Jul 23 15:33 makefile
-rw-r--r--  1 cjr       1738 Jul 28 14:38 param
-rw-r--r--  1 cjr       1269 Jul 23 14:47 pleq.f
-rw-r--r--  1 cjr      5321 Jul 23 14:48 quadpts.f
-rw-r--r--  1 cjr      3410 Jul 23 14:48 scatter.f
-rw-r--r--  1 cjr        307 Nov 17 1994 second.f
-rw-r--r--  1 cjr       1826 Jul 23 14:48 triangeh.f
```

-rw-r--r--	1	cjr	3137	Jul	23	14:49	triangej.f
-rw-r--r--	1	cjr	3321	Jul	23	14:49	triangej0.f
-rw-r--r--	1	cjr	2681	Jul	23	14:50	triangej01.f
-rw-r--r--	1	cjr	3494	Jul	23	14:51	triangem.f
-rw-r--r--	1	cjr	2082	Jul	23	14:51	triangem0.f
-rw-r--r--	1	cjr	1572	Jul	23	14:51	unorm.f
-rw-r--r--	1	cjr	856	Jul	23	14:53	vcross.f
-rw-r--r--	1	cjr	768	Jul	23	14:53	vdot.f
-rw-r--r--	1	cjr	5028	Jul	23	14:54	zmatrixeh.f
-rw-r--r--	1	cjr	8817	Jul	23	15:46	zmatrixej.f
-rw-r--r--	1	cjr	7591	Jul	23	15:46	zmatrixem.f

/FEMOM3DS-1.0/Example1

total 192

-rw-r--r--	1	cjr	40	Jul	24	09:34	input
-rw-r--r--	1	cjr	22	Jul	23	15:05	sp.MAT
-rw-r--r--	1	cjr	10590	Jul	29	11:01	sp.MOD
-rw-r--r--	1	cjr	2051	Jul	29	11:04	sp.OUT
-rw-r--r--	1	cjr	19698	Jul	29	11:02	sp.PIN
-rw-r--r--	1	cjr	561	Jul	29	11:02	sp.POUT
-rw-r--r--	1	cjr	472	Jul	29	11:01	sp.SES
-rw-r--r--	1	cjr	80	Jul	29	11:04	sp_bicgd.DAT
-rw-r--r--	1	cjr	41054	Jul	29	11:02	sp_edges.DAT
-rw-r--r--	1	cjr	10873	Jul	29	11:02	sp_nodal.DAT
-rw-r--r--	1	cjr	38262	Jul	29	11:02	sp_surfed.DAT

/FEMOM3DS-1.0/Example2

total 264

-rw-r--r--	1	cjr	22	Jul	24	09:08	inlet.MAT
-rw-r--r--	1	cjr	20748	Jul	28	14:32	inlet.MOD
-rw-r--r--	1	cjr	2229	Jul	28	16:59	inlet.OUT
-rw-r--r--	1	cjr	38377	Jul	29	08:20	inlet.PIN
-rw-r--r--	1	cjr	561	Jul	29	08:20	inlet.POUT
-rw-r--r--	1	cjr	551	Jul	28	14:33	inlet.SES
-rw-r--r--	1	cjr	1520	Jul	28	16:59	inlet_bicgd.DAT
-rw-r--r--	1	cjr	74008	Jul	29	08:20	inlet_edges.DAT
-rw-r--r--	1	cjr	22352	Jul	29	08:20	inlet_nodal.DAT
-rw-r--r--	1	cjr	49110	Jul	29	08:20	inlet_surfed.DAT
-rw-r--r--	1	cjr	28	Jul	28	14:34	input

Appendix 3

Sample *.SES files of COSMOS/M

The geometry modelling and meshing can be accomplished by using COSMOS/M. A variety of commands are available to define geometries. The constructed geometry is meshed and the mesh data can be written to a file with the `Modinput` command. Dielectric materials are identified by using material property command before meshing the corresponding part of the dielectric material. These are used as indices to tetrahedral elements, which will correspond to an entry in the *problem*.MAT file. Specification of the surfaces which are perfectly conducting, surfaces forming the radiating aperture and the input plane is accomplished by enforcing pressure boundary conditions on respective surfaces. Before the pressure condition is specified, a load condition has to be defined to indicate what type of surface is being specified. Load conditions of 1, 2, and 3 corresponds to perfectly conducting surface, surface with equivalent electric current and surface with equivalent magnetic current, respectively.

The *.SES files for the sample runs presented in section 4 are given below.

Example 1:

```
C*
C*  COSMOS/M          Geostar V1.75
C*  Problem : sp          Date :   7-29-97   Time :   8:32:50
C*
PT 1  0.000000  0.000000  0.000000
PT 2  0.000000  0.000000  0.16
PT 3  0.16  0.000000  0.000000
CRCIRCLE 1  1  2  3  0.160  90  1
CRCIRCLE 2  1  2  4  0.160  90  1
SFSWEEP 1  2  1  X  360.000000  4
PH 1  SF 1  0.1  0.001000  1
SCALE 0.000000
PART 1  1  1
CLS 1
PARTPLOT 1  1  1
MA_PART 1  1  1  1  0  4
ACTSET LC 1
ACTSET LC 2
```

```

PSF 1 2 8 1 2 2 4
ACTSET LC 3
PSF 1 3 8 1 3 3 4

```

Example 2:

```

C*
C*  COSMOS/M          Geostar V1.75
C*  Problem : inlet          Date : 7-24-97   Time : 9:39: 5
C*
SF4CORD 1 -0.15 -0.15 -0.1 0.15 -0.15 -0.1 0.15 0.15 -0.1 -0.15
0.15 &
-0.1
PLANE Z 0 1
VIEW 0 0 1 0
SCALE 0
VLEXTR 1 1 1 Z 0.2
PLANE Z 0 1
VIEW 1 1 1 0
SCALE 0
PH 1 SF 1 0.08 0.0001 1
PART 1 1 1
MA_PART 1 1 1 1 0 4
NMERGE 1 101 1 0.0001 0 0 0
NCOMPRESS 1 101
CLS 1
CLS 1
CLS 1
ACTSET LC 1
PSF 1 1 1 1 1 1 4
PSF 3 1 6 1 1 1 4
ACTSET LC 2
PSF 1 2 6 1 2 2 4
ACTSET LC 3
PSF 2 3 2 1 3 3 4

```

Appendix 4

Generic Input file format for PRE_FEMOM3DS

The following is the format of the generic input file (problem.PIN) to be supplied to PRE_FEMOM3DS with required nodal data.

N_n	● N_n : Number of nodes
N_e	● N_e : Number of trahedral elements
N_p	● N_p : Number of triangular elemets on PEC surfaces
N_{a1}	● N_{a1} : Number of triangular elements on surface with equivalent electric current
N_{a2}	● N_{a2} : Number of triangular elements on surface with equivalent magnetic current
N_g	● N_g : Maximum number of material groups
x_1, y_1, z_1	Coordinates of the nodes 1,2,3..., N_n
x_2, y_2, z_2	
.	
.	
.	
$x_{N_p}, y_{N_p}, z_{N_p}$	
$n_{11}, n_{21}, n_{31}, n_{41}, mg(1)$	Node numbers connecting each tetrahedral element 1, 2, 3,, N_e , and material group index number for each element
$n_{12}, n_{22}, n_{32}, n_{42}, mg(2)$	
$n_{1N_e}, n_{2N_e}, n_{3N_e}, n_{4N_e}, mg(N_e)$	

$$N_{e1}, n_{11}, n_{21}, n_{31}$$

$$N_{e2}, n_{12}, n_{22}, n_{32}$$

·
·

$$N_{eN_p}, n_{1N_p}, n_{2N_p}, n_{3N_p}$$

Global number of the terahedral element with a triangular face on PEC surface

($N_{e1}, N_{e2}, \dots, N_{eN_p}$)

and three nodes connecting the triangular element

$$N_{e1}, n_{11}, n_{21}, n_{31}$$

$$N_{e2}, n_{12}, n_{22}, n_{32}$$

·
·
·
·

$$N_{eN_{a1}}, n_{1N_{a1}}, n_{2N_{a1}}, n_{3N_{a1}}$$

Global number of the terahedral element with a triangular face on the electric current surface

($N_{e1}, N_{e2}, \dots, N_{eN_{a1}}$)

and three nodes connecting the triangular element

$$N_{e1}, n_{11}, n_{21}, n_{31}$$

$$N_{e2}, n_{12}, n_{22}, n_{32}$$

·
·
·
·
·

$$N_{eN_{a2}}, n_{1N_{a2}}, n_{2N_{a2}}, n_{3N_{a2}}$$

Global number of the terahedral element with a triangular face on the magnetic current surface

($N_{e1}, N_{e2}, \dots, N_{eN_{a2}}$)

and three nodes connecting the triangular element

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